

HIGH-RESOLUTION VARIABLE ATTENUATION DEVICE

FIELD OF THE INVENTION

(001) This invention relates to attenuators and, more particularly, to digital planar RF attenuators.

BACKGROUND

(002) When verifying the proper operation of circuitry components, test equipment is often used to generate test signals that are provided to the components being tested. In order to ensure accurate verification, the characteristics of these test signals have to be controlled. Examples of these signal characteristics are signal type (e.g., DC, AC, sine wave, square wave, etc.), signal frequency, frequency sweep rate, signal amplitude, and amplitude sweep rate.

(003) Variable attenuators are often used to control signal amplitude. Examples of these variable attenuators include voltage-variable analog attenuators, PIN-diode attenuators, and digital attenuators (e.g., switched-bit digital attenuators).

(004) Voltage-variable analog attenuators typically include one or more field effect transistors that are controlled (via their gate voltage) to act like variable resistors in a series or a shunt configuration. PIN-diode attenuators typically forward bias a PIN diode so that they function as current-controlled resistors.

(005) Voltage-variable attenuators and PIN-diode attenuators may be controlled digitally with the combination of a DAC (i.e., digital-to-analog converter) and an operational amplifier. Unfortunately, even with digital control, voltage-variable and PIN-diode attenuators provide non-linear performance, require time and cost to calibrate, and increase the parts count per attenuator unit.

(006) While digital attenuators allow for direct digital control, these attenuators are typically too coarse, in that the highest-resolution achievable (i.e., the smallest amount of attenuation selectable) is between 0.25 and 0.50 decibels.

SUMMARY OF THE INVENTION

(007) According to an aspect of this invention, a variable attenuation device includes a resistive array having two or more input nodes, two or more output nodes, and two or more resistive devices for coupling the input nodes and the output nodes. A first switch has an input terminal and two or more selectable output terminals, such that the input terminal is configured to receive an input signal and the two or more selectable output terminals are coupled to the two or more input nodes of the resistive array. A second switch has two or more selectable input terminals and an output terminal, such that the output terminal is configured to provide an attenuated output signal and the two or more selectable input terminals are coupled to the two or more output nodes of the resistive array. The output terminal selected on the first switch and the input terminal selected on the second switch varies the resistance seen by the input signal, and the values of the two or more resistive devices are configured to allow for substantially uniform attenuation steps of the input signal.

(008) One or more of the following features may also be included. The first and/or second switch may include a discrete switching device (e.g., one or more discrete transistors or one or more transistors formed in a semiconductor substrate) coupled to each of the selectable output/input terminals. The input signal may be an RF signal.

(009) The resistive devices may be discrete resistors, or formed with resistive material deposited on a semiconductor, dielectric, or insulating substrate. The resistive array may be a planar resistive array, which may be formed with resistive material deposited on a semiconductor, dielectric, or insulating substrate.

(010) A first shunt resistance may couple the input terminal of the first switch to a ground, and a second shunt resistance may couple the output terminal of the second switch to the ground.

(011) At least one of the resistive devices of the resistive array may connect two of

the input nodes of the resistive array, or may connect one of the input nodes to one of the output nodes of the resistive array.

(012) The first and second switches may be reflective switches.

(013) According to a further aspect of this invention, a signal splitting system is provided by coupling a signal splitting device to the variable attenuation device described above. The signal splitting device is configured to receive an input signal on an input port and provide essentially equal output signals on each of a plurality of output ports,.

(014) According to a further aspect of this invention, a signal attenuation system is provided by coupling a low-resolution signal attenuation device (e.g., a PIN diode attenuator or a voltage-variable analog attenuator) to the variable attenuation device described above. The low-resolution signal attenuation device is configured to receive an input signal on an input port and provide a coarsely-attenuated (e.g., 0.50 dB step) output signal on an output port, and the variable attenuation device is configured to allow for substantially-uniform fine attenuation steps (e.g., 0.05 dB) of the coarsely-attenuated output signal.

(015) According to a further aspect of this invention, a testing system is provided by coupling a device-under-test to the variable attenuation device described above. The device-under-test includes an input port configured to receive a test signal that is provided by the variable attenuation device.

(016) According to a further aspect of this invention, a dual-switch shunt variable attenuation device includes a resistive array having two or more input nodes, two or more output nodes, and two or more resistive devices for coupling the input nodes and the output nodes. A first switch has an input terminal and two or more selectable output terminals, such that the input terminal is configured to receive an input signal and the two or more selectable output terminals are coupled to the two or more input nodes of the resistive array. A second switch has two or more selectable input terminals and an output terminal, such that the output terminal is coupled to a ground and the two or more

selectable input terminals are coupled to the two or more output nodes of the resistive array. The output terminal selected on the first switch and the input terminal selected on the second switch vary the resistance seen by the input signal, and the values of the two or more resistive devices are configured to allow for substantially-uniform attenuation steps of the input signal.

(017) According to a further aspect of this invention, a single-switch shunt variable attenuation device includes a resistive array having two or more input nodes, two or more output nodes coupled to a ground, and two or more resistive devices for coupling the input nodes and the output nodes. A first switch has an input terminal and two or more selectable output terminals, such that the input terminal is configured to receive an input signal and the two or more selectable output terminals are coupled to the two or more input nodes of the resistive array. The output terminal selected on the first switch varies the resistance seen by the input signal, and the values of the two or more resistive devices are configured to allow for substantially-uniform attenuation steps of the input signal.

(018) The details of one or more implementations are set forth in the accompanying drawings and the description below. Other features and advantages will become apparent from the description, the drawings, and the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

(019) FIG. 1 is a block diagram of a series variable attenuation device;

(020) FIG. 2 is a schematic diagram of the switch of the variable attenuation device of FIG. 1;

(021) FIG. 3 is a block diagram of a signal splitting system including a signal splitter and an attenuator;

(022) FIG. 4 is a block diagram of a signal attenuation system including a low-resolution attenuator and a high-resolution attenuator;

(023) FIG. 5 is a block diagram of a testing system including an attenuator and a device-under-test;

(024) FIG. 6 is a block diagram of a series variable attenuation device including two-way switches;

(025) FIG. 7 is a block diagram of a series variable attenuation device including three-way switches;

(026) FIG. 8 is a block diagram of a series variable attenuation device including five-way switches;

(027) FIG. 9 is a block diagram of a dual-switch shunt variable attenuation device; and

(028) FIG. 10 is a block diagram of a single-switch shunt variable attenuation device.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

(029) Referring to FIG. 1, there is shown a variable attenuation device 10 for receiving a input signal 12, such as an RF (i.e., radio frequency) or microwave signal and providing an attenuated output signal 14.

(030) Variable attenuation device 10 includes a first switch 16, a second switch 18, and a resistive array 20. As will be discussed below, by controlling the position of switches 16 and 18, the level of attenuation experienced by input signal 12 is controllable.

(031) First switch 16 includes an input terminal 22 and four selectable output terminals 24, 26, 28 and 30. Output terminals 24, 26, 28 and 30 are coupled to the input nodes 32, 34, 36 and 38 of resistive array 20.

(032) Resistive array 20 includes multiple resistors R1 - R7 that provide resistive paths between input nodes 32, 34, 36 and 38 and output nodes 54, 56, 58 and 60 of resistive array 20. These resistors may be connected between an input and an output

node (e.g., resistor R1), between input nodes (e.g., resistor R2), or between output nodes (not shown). Typically, resistive array 20 is a planar resistive array in which the various signal paths between input nodes 32, 34, 36 and 38 and output nodes 54, 56, 58 and 60 do not cross each other, thus reducing the possibility of deleterious effects at higher input signal frequencies.

(033) Second switch 18 includes an output terminal 62 and four selectable input terminals 64, 66, 68 and 70 that are coupled to the output nodes 54, 56, 58 and 60 of resistive array 20.

(034) Switches 16 and 18 are configured to receive control signals 72 and 74 (respectively), which are typically digital control signals (to be discussed below). Control signal 72 controls which of the output terminals 24, 26, 28 or 30 of first switch 16 are selected, and control signal 74 controls which of the input terminals 64, 66, 68 and 70 of second switch 18 are selected.

(035) Switches 16 and 18 are typically reflective RF switches, as opposed to non-reflective RF switches. A non-reflective RF switch (also known as an absorptive RF switch) has internal load terminations that terminate any non-selected input or output terminals on the switch, thus absorbing any signal on that terminal. Conversely, reflective RF switches do not have internal load terminations and, therefore, non-selected input or output terminals float. This configuration prevents absorption and allows for reflection of the signal.

(036) During operation of variable attenuation device 10, by manipulating the position of switches 16 and 18, the resistive load seen by input signal 12 can be varied. For example, if resistors R1, R2, R4, and R6 are 1.0 ohm resistors, resistor R3 is a 3.0 ohm resistor, resistor R5 is a 5.0 ohm resistor, and resistor R7 is a 7.0 ohm resistor, total resistances between 1.0 ohm and 10.0 ohms are possible. In this example, if input signal 12 is routed from input node 32 to output node 54 of resistive array 20, a resistive load of 1.0 ohm is realized. Alternatively, if input signal 12 is routed from input node

32 to output node 60, a resistive load of 10.0 ohms is realized.

(037) By carefully choosing the value of resistors R1-R7, substantially uniform attenuation steps can be achieved. This is best explained with the following example. Concerning the four-way switch implementation described above and a desired 0.05 attenuation step, assume the resistors are chosen as follows: R1 is 0.593 ohms; R2 is 1.779 ohms; R3 is 1.779 ohms; R4 is 2.372 ohms; R5 is 2.965 ohms; R6 is 2.372 ohms; and R7 is 1.186 ohms. As this particular implementation uses four-way switches, there are 4^2 or sixteen possible switch combinations, some of which result in duplicate load impedances.

Path	Total Resistance (Z _l)	Attenuation (dB)	Delta (dB)	ABS value
R1	0.593 ohms	-0.05136	-0.00136	0.00136
R2+R3	3.558 ohms	-0.30367	-0.00367	0.00367
R2+R4+R5	7.116 ohms	-0.59709	0.00291	0.00291
R2+R4+R6+R7	7.709 ohms	-0.64504	0.00496	0.00496
R2+R1	2.372 ohms	-0.20362	-0.00362	0.00362
R3	1.779 ohms	-0.15316	-0.00316	0.00316
R4+R5	5.337 ohms	-0.45162	-0.00162	0.00162
R4+R6+R7	5.930 ohms	-0.50038	-0.00038	0.00038
R4+R2+R1	4.744 ohms	-0.40258	-0.00258	0.00258
R4+R3	4.151 ohms	-0.35327	-0.00327	0.00327
R5	2.965 ohms	-0.25379	-0.00379	0.00379
R6+R7	3.558 ohms	-0.30367	-0.00367	0.00367
R6+R4+R2+R1	7.116 ohms	-0.59709	0.00291	0.00291
R6+R4+R3	6.523 ohms	-0.54887	0.00113	0.00113
R6+R5	5.337 ohms	-0.45162	-0.00162	0.00162
R7	1.186 ohms	-0.10241	-0.00241	0.00241

(038) For the above table, the attenuation is determined using the following formula:

$$\text{Attenuation(dB)} = 20 \log \left[\frac{2}{2 + (Z_l / Z_i)} \right]$$

(039) The "Z_i" in the denominator of the above formula represents the impedance of the transmission line providing input signal 12. For the above table, Z_i was set to 50 ohms. The Delta (dB) represents the variation from a defined attenuation step. For the above table, the resistance values were determined empirically so that attenuation steps of

0.05 decibels are defined. Therefore, the defined attenuation steps are 0.05 dB, 0.10 dB, 0.15 dB, 0.20dB, and so on, continuing up to 0.65 dB. The Delta (dB) represents the actual variation from a defined attenuation step, and the ABS(dB) represents the absolute value of the Delta (dB). For the above table, Delta (dB) has an average value of -0.001203 dB, which represents an average error (with respect to the defined attenuation steps) of 2.41%.

(040) While the above table defines the resistance values that result in stepped attenuation values of 0.05 decibels, by scaling the above-defined resistance values up or down, the attenuation step size can be increased or decreased respectively.

(041) Shunt resistances R8 and R9 may be included to couple input terminal 22 and output terminal 62 (respectively) to ground. The use of shunt resistances allows for better impedance matching by reducing the portion of the input signal 12 that is reflected. For the above-described four-way 0.05 decibel attenuation step system, a typical value for shunt resistances R8 and R9 is 1,800 ohms.

(042) Resistors R1-R9 may be discrete resistors that are attached to a printed circuit board. Alternatively, resistors R1-R9 may be formed by depositing resistive material on a semiconductor, dielectric, or insulating substrate .

(043) Switches 16 and 18 are typically implemented using RF transistors. Referring to FIG. 2, an implementation of switch 16 is shown that includes four transistors 100, 102, 104 and 106, each of which is controlled with a separate control signal 108, 110, 112 and 114 (respectively) applied to the gate of the transistor. In this embodiment, control signal 72 is actually four separate signals, one of which controls the state of each transistor. Alternatively, a two bit bus may be used to select one of the four possible switch states. Accordingly, applying a gate voltage to a transistor controls the conductive state of the transistor. This, in turn, may allow input signal 12 to pass through the selected transistor and appear on the appropriate output terminal 24, 26, 28 or 30.

(044) Transistors 100, 102, 104 and 106 may be discrete transistors attached to a printed circuit board or may be IC (i.e., integrated circuit) transistors that are formed in a semiconductor substrate. As is known in the art, RF switches (e.g., switch 16) may be constructed using both series and shunt transistors configurations.

(045) Referring to FIG. 3, there is shown variable attenuation device 10 being used in combination with a signal splitter 120. An example of signal splitter 120 is an RF6400 four port splitter module produced by the LTX Corporation of Westwood, Massachusetts. Splitter 120 receives (on an input port) input signal 12 from a signal source (not shown) and provides (on output port) four essentially equal signals 122, 124, 126 and 128. However, due to variations and tolerances in the components used to couple splitter 120 and variable attenuation device 10 (three of which are shown), the strength of each of these signals typically varies. Accordingly, once a determination is made concerning which of the signals is the weakest (i.e., signal 128), a variable attenuation device 10 may be used to attenuate each of the other signals (i.e., signals 122, 124 and 126) to make them equal in strength to that of the weakest signal. Alternatively, a fourth attenuator (not shown) may be coupled to signal 128 to compensate for frequency-dependant signal strength variations.

(046) Referring to FIG. 4, there is shown a variable attenuation device 10 (i.e., a high-resolution attenuator) being used in series with a low resolution attenuator 140. Low resolution attenuator 140 (e.g., a voltage-variable attenuator, a PIN-diode attenuator, a switched-bit digital attenuator; described above) receives input signal 12 on an input port and provides (on an output port) a coarsely-attenuated signal 142 having attenuation steps in the range of 0.25-0.50 decibels. This coarsely-attenuated signal is provided to variable attenuation device 10 so that the signal can be "fine tuned" to generate a finely-attenuated output signal 144. By using the resistor values defined above for variable attenuation device 10, an attenuation resolution (i.e., attenuation step size) of 0.05 decibels is realized. Further, as described above, by equally scaling all of the

resistor values down, a higher resolution (i.e., a smaller attenuation step size) can be achieved.

(047) Referring to FIG. 5, there is shown a variable attenuation device 10 being used to provide a test signal (i.e., attenuated output signal 14) to a device-under-test 160. Examples of device under test 160 include receiver circuits, down-converter mixers, and low-noise amplifiers. During use, input signal 12 is attenuated using variable attenuation device 10, generating attenuated output signal 14 that is provided to device-under-test 160.

(048) While the resistive array is described above as including four input nodes and four output nodes, other configurations are possible. For example, since the number of nodes in the resistive array typically match the number of selectable outputs or inputs of the switch(es) of the system, the use of an "N"-way switch typically results in a resistive array having "N" input and output nodes.

(049) While the first switch and the second switch are shown as four-way switches (i.e., having four outputs or four input), other configurations are possible (as described below).

(050) Referring to FIG. 6, there is shown a variable attenuation device 180 that includes a pair of two-way switches 182 and 184, and three resistors R1-R3. As with the above described system, by varying the position of switches 182 and 184, the level of attenuation experienced by input signal 12 is controllable. Again, by carefully choosing the value of resistors R1-R3, substantially uniform attenuation steps can be achieved.

(051) Concerning this two-way switch implementation, for a desired 0.05 dB attenuation step, assume the resistors are chosen as follows: R1 is 1.164 ohms; R2 is 1.164 ohms; and R3 is 0.582. As this particular implementation uses two-way switches, there are 2^2 or four possible switch combinations.

Path	Total Resistance (Z_t)	Attenuation (dB)	Delta (dB)	ABS value
R1	1.164 ohms	-0.10052	-0.00052	0.00052

R2+R3	1.746 ohms	-0.15035	-0.00035	0.00035
R2+R1	2.328 ohms	-0.19989	0.00011	0.00011
R3	0.582 ohms	-0.05041	-0.00041	0.00041

(052) As above, the attenuation is determined using the following formula:

$$\text{Attenuation(db)} = 20 \log \left[\frac{2}{2 + (Z_t / Z_l)} \right]$$

(053) Setting Z_l equal to 50 ohms for this two-way switch system, the defined attenuation steps are 0.05 dB, 0.10 dB, 0.15 dB and 0.20dB. Delta (dB) has an average value of -0.000290 dB, which represents an average error (with respect to the defined attenuation steps) of 0.58%.

(054) Referring to FIG. 7, there is shown a variable attenuation device 200 that includes a pair of three-way switches 202 and 204, and five resistors R1-R5. As with the above described systems, by varying the position of switches 202 and 204, the level of attenuation experienced by input signal 12 is controllable. Again, by carefully choosing the value of resistors R1-R5, substantially uniform attenuation steps can be achieved.

(055) Thus far, the desired attenuation step has been set to 0.05 dB. However, as stated above, this value can be increased or decreased as needed or desired. Concerning this three-way switch implementation, for a desired 0.10 dB attenuation step, assume the resistors are chosen as follows: R1 is 0.586 ohms; R2 is 2.344 ohms; R3 is 5.274 ohms; R4 is 1.172 ohms; and R5 is 0.586 ohms. As this particular implementation uses three-way switches, there are 3^2 or nine possible switch combinations, some of which result in duplicate load impedances.

Path	Total Resistance (Z_t)	Attenuation (dB)	Delta (dB)	ABS value
R1	0.586 ohms	-0.05075	-0.00075	0.00075
R2+R3	7.618 ohms	-0.63770	0.01230	0.01230
R2+R4+R5	4.102 ohms	-0.34918	0.00082	0.00082
R2+R1	2.930 ohms	-0.25084	-0.00084	0.00084
R3	5.274 ohms	-0.44642	-0.00358	0.00358
R5+R4	1.758 ohms	-0.15137	-0.00137	0.00137

R4+R2+R1	4.102 ohms	-0.34918	0.00082	0.00082
R4+R3	6.446 ohms	-0.54259	0.00741	0.00741
R5	0.586 ohms	-0.05075	-0.00075	0.00075

(056) As above, the attenuation is determined using the following formula:

$$\text{Attenuation(dB)} = 20 \log \left[\frac{2}{2 + (Z_t / Z_i)} \right]$$

(057) Setting Z_i equal to 50 ohms for this three-way switch system, the defined attenuation steps are 0.05 dB, 0.15 dB, 0.25 dB, 0.35 dB, 0.45 dB, 0.55 dB and 0.65 dB. Delta (dB) has an average value of 0.002357 dB, which represents an average error (with respect to the defined attenuation steps) of 2.36%.

(058) Referring to FIG. 8, there is shown a variable attenuation device 220 that includes a pair of five-way switches 222 and 224, and nine resistors R1-R9. As with the above described systems, by varying the position of switches 222 and 224, the level of attenuation experienced by input signal 12 is controllable. Again, by carefully choosing the value of resistors R1-R9, substantially uniform attenuation steps can be achieved.

(059) Concerning this five-way switch implementation, for a desired 0.05 dB attenuation step, assume the resistors are chosen as follows: R1 is 0.599 ohms; R2 is 2.396 ohms; R3 is 1.797 ohms; R4 is 1.180 ohms; R5 is 3.594 ohms; R6 is 1.797 ohms; R7 is 1.797 ohms, R8 is 1.797 ohms; and R9 is 0.599 ohms. As this particular implementation uses five-way switches, there are 5^2 or twenty-five possible switch combinations, some of which result in duplicate load impedances.

Path	Total Resistance (Z_t)	Attenuation (dB)	Delta (dB)	ABS value
R1	0.599 ohms	-0.05187	-0.00187	0.00187
R2+R3	4.193 ohms	-0.35677	-0.00677	0.00677
R2+R7+R4	5.391 ohms	-0.45607	-0.00607	0.00607
R2+R7+R5+R6	9.584 ohms	-0.79494	0.00506	0.00506
R2+R7+R5+R8+R9	10.183 ohms	-0.84229	0.00771	0.00771
R2+R1	2.995 ohms	-0.25632	-0.00632	0.00632
R3	1.797 ohms	-0.15470	-0.00470	0.00470
R7+R4	2.995 ohms	-0.25632	-0.00632	0.00632
R7+R5+R6	7.188 ohms	-0.60292	-0.00292	0.00292

R7+R5+R8+R9	7.787 ohms	-0.65133	-0.00133	0.00133
R7+R2+R1	4.792 ohms	-0.40656	-0.00656	0.00656
R7+R3	3.594 ohms	-0.30669	-0.00669	0.00669
R4	1.198 ohms	-0.10344	-0.00344	0.00344
R5+R6	5.391 ohms	-0.45607	-0.00607	0.00607
R5+R8+R9	5.990 ohms	-0.50530	-0.00530	0.00530
R5+R7+R2+R1	8.386 ohms	-0.69946	0.00054	0.00054
R5+R7+R3	7.188 ohms	-0.60292	-0.00292	0.00292
R5+R4	4.792 ohms	-0.40656	-0.00656	0.00656
R6	1.797 ohms	-0.15470	-0.00470	0.00470
R8+R9	2.396 ohms	-0.20566	-0.00566	0.00566
R9	0.599 ohms	-0.05187	-0.00187	0.00187
R8+R6	3.594 ohms	-0.30669	-0.00669	0.00669
R8+R5+R4	6.589 ohms	-0.55425	-0.00425	0.00425
R8+R5+R7+R3	8.985 ohms	-0.74733	0.00267	0.00267
R8+R5+R7+R2+R1	10.183 ohms	-0.84229	0.00771	0.00771

(060) As above, the attenuation is determined using the following formula:

$$\text{Attenuation(dB)} = 20 \log \left[\frac{2}{2 + (Z_i / Z_l)} \right]$$

(061) Setting Z_l equal to 50 ohms for this five-way switch system, the defined attenuation steps are 0.05 dB, 0.10 dB, 0.15 dB, 0.20 dB, 0.25 dB, and so on, continuing up to 0.85 dB. Delta (dB) has an average value of -0.002934 dB, which represents an average error (with respect to the defined attenuation steps) of 5.87%.

(062) While, thus far, the variable attenuation devices have been described as being used in a series configuration (with respect to the input signal), other configurations are possible. For example, the variable attenuation devices may be used in a shunt configuration.

(063) Referring to FIG. 9, there is shown a dual-switch shunt variable attenuation device 240 that includes a pair of four-way switches 242 and 244 and seven resistors R1-R7. While schematically similar to the dual-switch series variable attenuation device of FIG. 1, the output terminal 246 of the shunt device 240 is tied to ground. Therefore, by varying the position of switches 242 and 244, the shunt load experienced by input signal 12 is varied, resulting in a variation of the attenuation experienced by

input signal 12. As above, by carefully choosing the value of resistors R1-R7, substantially uniform attenuation steps can be achieved.

(064) Referring to FIG. 10, there is shown a single-switch shunt variable attenuation device 260. While schematically similar to the dual-switch shunt variable attenuation device of FIG. 8, only a single switch 262 is used and, therefore, the output nodes 264, 266, 268 and 270 are tied to ground. Therefore, by varying the position of switch 262, the shunt load experienced by the input signal is varied, resulting in a variation of the attenuation experienced by the input signal. As above, by carefully choosing the value of resistors R1-R7, substantially uniform attenuation steps can be achieved. However, while this configuration has a reduced parts count, as there is only one switch, the maximum number of shunt loads is never greater than the number of switch positions for switch 262.

(065) While the system is described above as separate components (e.g., two switches and a resistor array), other configurations are possible. For example, the entire device may be formed on a single integrated circuit chip.

(066) A number of implementations have been described. Nevertheless, it will be understood that various modifications may be made. Accordingly, other implementations are within the scope of the following claims.